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DR JEFFREY P BONS

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Department of Mechanical Engineering
Brigham Young University
Provo Utah

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Final Technical Report

INTEGRATED FLOW CONTROL DEVICES FOR THE DESIGN OF ENHANCED LOW PRESSURE TURBINES

AFOSR GRANT # F49620-03-1-0049

Jeffrey P. Bons
Department of Mechanical Engineering
Brigham Young University
Provo, Utah

Short Abstract
Flow separation limits the efficiency of low-pressure turbines (LPTs) in aircraft engines. Recent experiments with vortex generator jets (VGJs), conducted in AFRL's low-speed cascade at Wright-Patterson AFB, have demonstrated dramatic reductions in separation losses. The critical science that will enable this design innovation to reach its potential is a comprehensive understanding of the effect of VGJs on a separating boundary layer. Experiments are underway at BYU to better understand the basic physics of the separation control phenomenon and establish the quantitative links between the underlying flow physics and LPT performance. Two-component velocity measurements of VGJ evolution have been made along a flat wall with no freestream pressure gradient and at pressure gradient conditions typical of a low pressure turbine suction surface. Initial measurements are also being taken in a linear cascade for comparison with the flat wall studies. Data clearly show the presence of streamwise vortices which provide the necessary boundary layer mixing to inhibit separation. Vortex development is modified when jet injection occurs in an adverse pressure gradient. The effects of freestream turbulence will also be considered. These detailed flow measurements are suitable for code validation.

Main Abstract
Objectives: Flow separation limits the efficiency of modern low-pressure turbines in aircraft gas turbine engines. Recent experiments with vortex generator jets, conducted in AFRL's cascade at Wright-Patterson AFB, demonstrated reductions in separation losses at low Reynolds numbers [1]. This was followed by demonstrations of VGJ separation control at higher Reynolds numbers but with increased blade pitch (ie...fewer blades) [2]. This proof-of-concept demonstrated the potential to design highly-loaded, compact, LPTs with integrated flow control using VGJs. The objective of this research is to understand the fundamental physics of this interaction so that VGJ models can be developed and incorporated into existing LPT design codes. To achieve the required level of flow understanding will require the coupling of experimental, computational, and analytical design studies. As such, detailed flow measurements accomplished at BYU as part of this research are available for code validation elsewhere. The combination of experiment

and computation will form the building blocks for understanding the basic physics of the separation control phenomenon, with the results feeding directly into the continuing AFOSR design task of Drs. Rolf Sondergaard and Richard Rivir at AFRL/PRTT.

Approach: Experimental measurements are underway in a modular wind tunnel facility at Brigham Young University. The wind tunnel can be operated in any of four configurations: flat wall no pressure gradient, flat wall with pressure gradient, curved wall no pressure gradient, full LPT cascade with wall curvature and pressure gradient. This sequence allows the independent evaluation of streamwise pressure gradient and wall curvature and their effects on VGJs. A 3-axis traverse system mounted atop the tunnel is used to make two-component velocity measurements using split-film anemometry. Planes of velocity measurements before and after jet injection chart the jet evolution and modifications to the boundary layer. The data format is suitable for comparisons with CFD simulations.

Progress: During this reporting period, initial flow quality assessments were conducted in the new wind tunnel facility. Excellent flow uniformity (within ±2%) was achieved in the tunnel with a background freestream turbulence level below 0.3%. This freestream turbulence level can be augmented using a blown grid to levels from 3% (passive) to 12% (active). When operated with low freestream turbulence and no streamwise pressure gradient, the boundary layer development follows the classical Blasius profile. Testing has been completed with the flat wall no pressure gradient configuration. The test matrix included 3 blowing ratios (B = V_{jet}/V_∞ = 0, 2,& 4), 3 Reynolds numbers (equivalent to cascade Re = 25000, 50000, and 75000 – based on blade axial chord, C_x, and inlet conditions), and 2 boundary layer states (laminar and tripped turbulent). The second configuration studied was the flat wall with pressure gradient. A wedge with aft suction (Figure 1) was inserted into the straight wind tunnel test section to provide a streamwise pressure distribution matching that found in the AFRL Pak-B cascade facility (Figure 2). The test matrix thus far has included 3 blowing ratios, 2 Reynolds numbers, and 2 VGJ locations (equivalent C_x = 61% and 69%) with a laminar boundary layer.
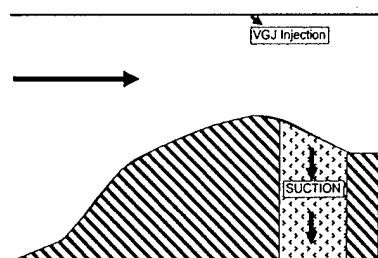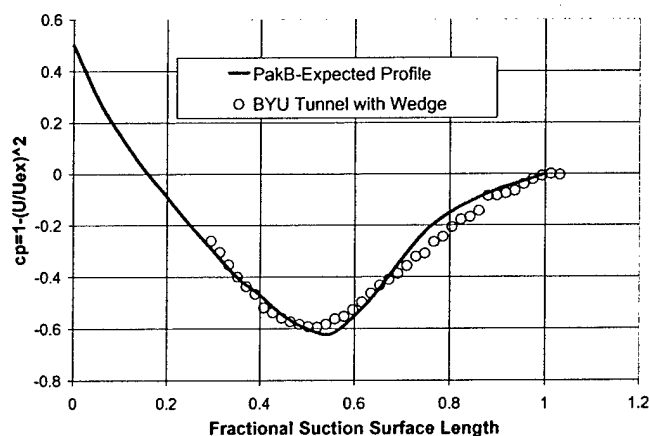

Figure 1: Wedge Schematic

Figure 2: Comparison of cp for variable pressure gradient tunnel with Pak-B calculation.

Finally, the 3-blade cascade configuration (Figure 3) has been completed and testing is underway.
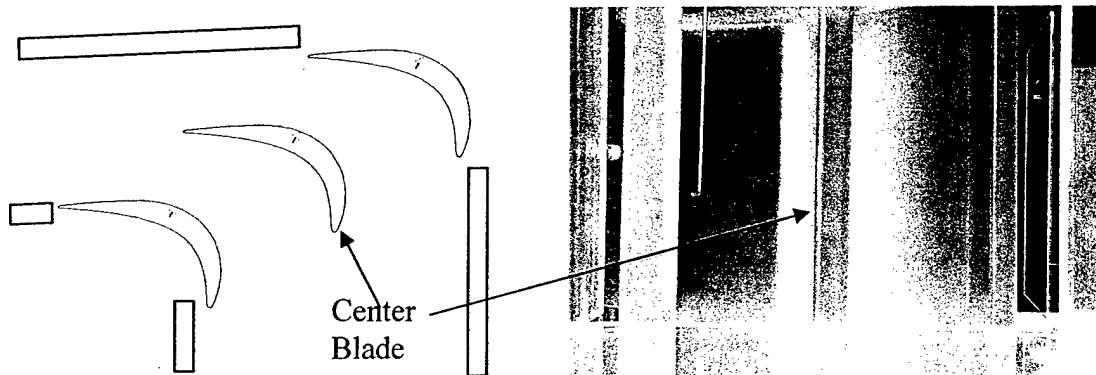

Figure 3: Schematic of 3-blade cascade configuration with photo of installed blades.

Results: One of the primary motivations for these experiments is the limited access in the large AFRL cascade facility. The 1.2m x 0.85m, 9-blade cascade and small VGJ hole diameter (1mm) make detailed flow studies difficult. The success of the VGJs has been attributed to the creation of streamwise vortices that enhance mixing between the freestream and boundary layer [1], but no evidence of vortices was ever produced. As such, boundary layer transition could not be altogether ruled out as a possible mechanism. There was some evidence that the jets are not simply a boundary layer trip since the resultant boundary layer looked different and a passive trip was not effective at increased blade pitch while the VGJs were [2]. However, streamwise vortices were never measured. As such, the first data from the straight tunnel configuration documents the formation of streamwise vortices, one per VGJ hole, as shown in Figure 5.

(a) u/Ue, x/d=10

(b) u/Ue, x/d=40

(c) v/Ue, x/d=10

(d) v/Ue, x/d=40
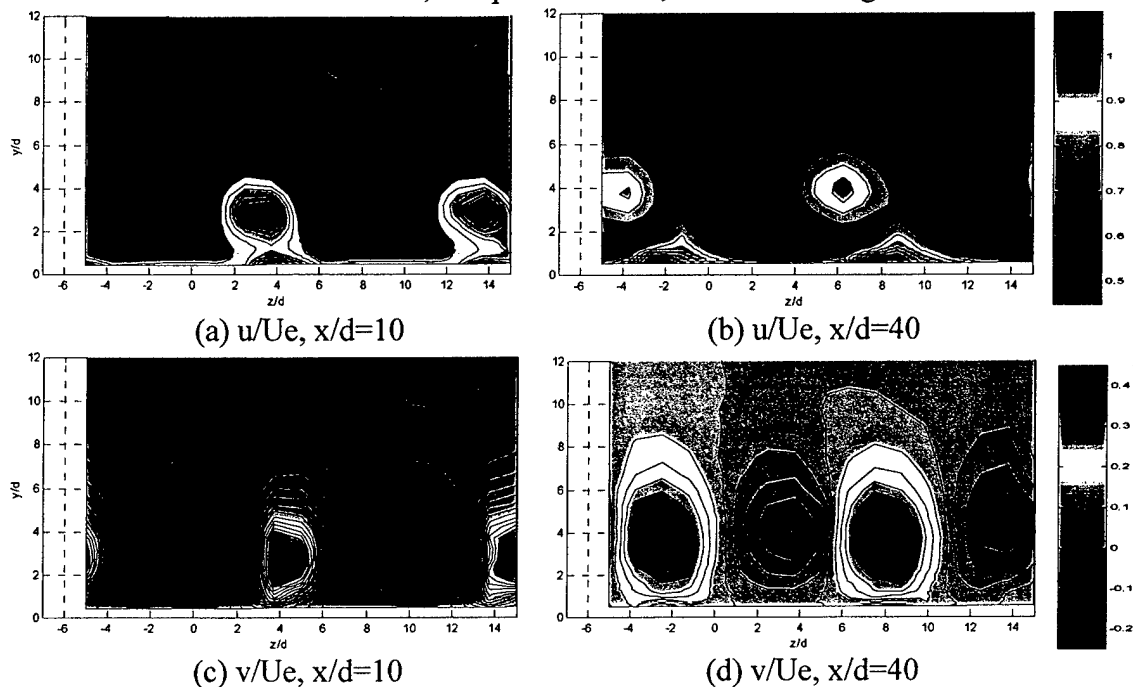
Figures 4a-d: Contour maps of streamwise (u/Ue) and wall normal (v/Ue) velocity components at x/d = 10 and 40. Data is shown looking upstream at the jets, injected at z/d = 0. VGJ pitch is 30deg from horizontal in the direction of +z/d (jet skew angle is

90deg from the freestream direction). Equivalent Re = 50000 and B = 4 into a laminar boundary layer with flat wall and zero pressure gradient.

The u/U_e contour maps clearly show the location of VGJ fluid, which has a lower velocity than the freestream due to its skewed injection (with zero streamwise momentum). The jet is coherent well downstream of the injection point in this configuration. The v/U_e maps clearly show the existence of the streamwise vortex near the VGJ fluid residue. By plotting u/U_e and v/U_e along a horizontal line through the core of the jet fluid, the relative position of the vortex and jet centers can be shown (Figure 5). The jet core position slightly to the right of the vortex center is consistent with the schematic depicting jet injection and vortex formation. The small vortex under the jet injection is visible at x/d=10 for B=2 but is quickly consumed in the boundary layer.
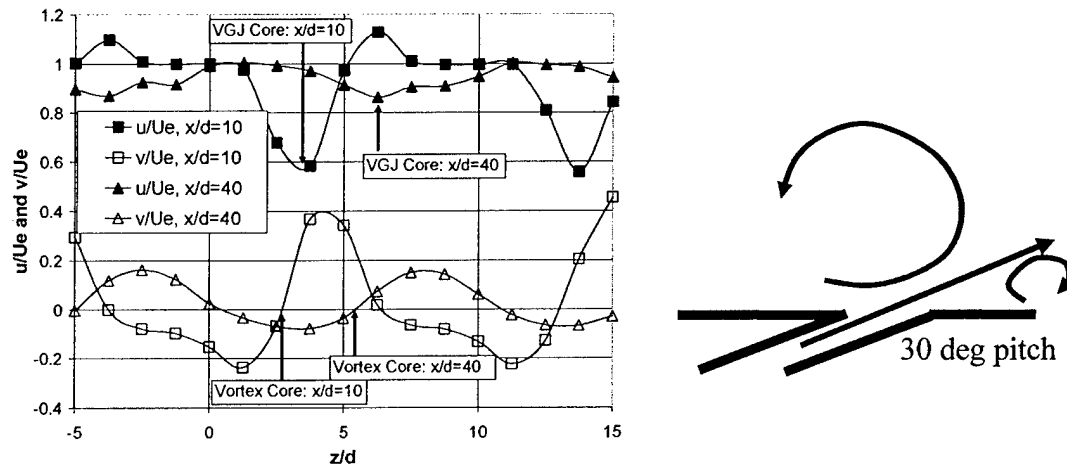

Figure 5: Plot of streamwise (u/U_e) and wall normal (v/U_e) velocity components vs. z/d at x/d = 10 and 40. Data is taken at constant y/d through the center of the jet cores in Figure 4. Schematic shows the VGJ injection and vortex development.

That this vortex performs the desired function of moving boundary layer fluid away from the wall and replacing it with freestream fluid is evident from contour maps of the Reynolds stress term, u'v' (Figure 6).
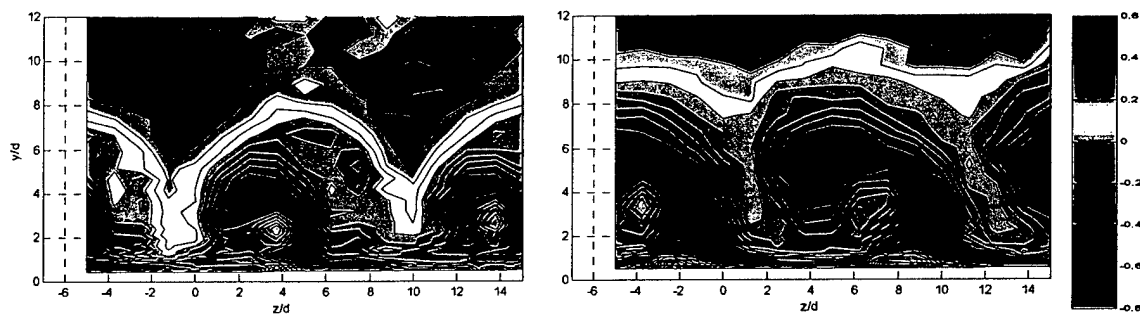

Figure 6: Contour maps of Reynolds stress ($u'v'/u_{rms}v_{rms}$) at x/d = 10 and 40. Data is shown looking upstream at the jets, injected at z/d = 0. Identical conditions to Figure 5.

This Reynolds stress has a negative sign in the boundary layer where du/dy > 0. Figure 7 clearly shows this negative Reynolds stress fluid being drawn by the vortex away from the wall. The net result is a reenergized boundary layer, as shown in the ensemble-

averaged boundary layer profiles of Figure 7a. Incidentally, this plot is similar to data acquired at a single location downstream of VGJs in the AFRL cascade. Due to the small hole size (1mm) and relatively large hot-wire sensor (~2mm), the measured velocity at AFRL was an area average across the jet. The 4 mm hole diameter used in the BYU tunnel permits detailed flow measurement with the split-film probe as shown here.
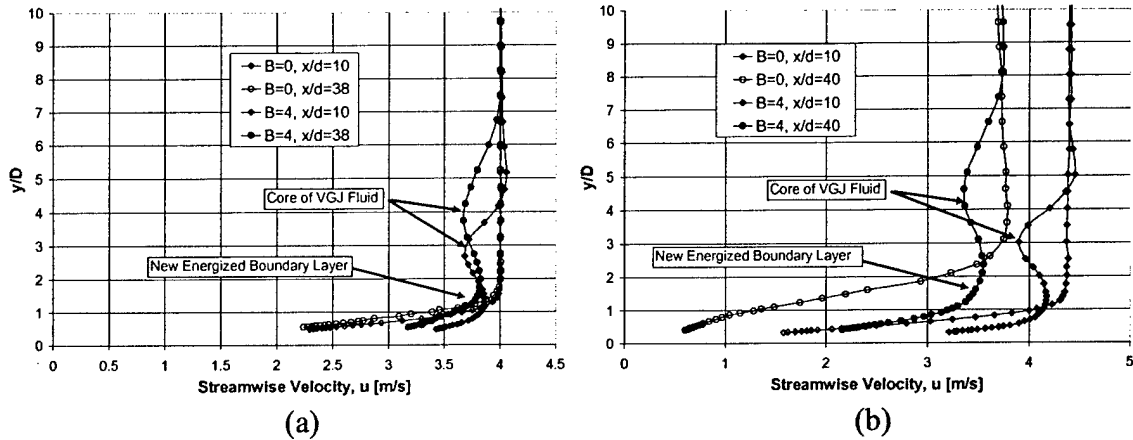

(a)   (b)

Figure 7a&b: Plot of u/Ue vs. y/d at x/d = 10 and 40. Data is ensemble average of 17 boundary layer profiles across 2 hole pitches for (a) Figure 4 flow conditions with no pressure gradient and (b) comparable flow conditions with adverse pressure gradient.

In the adverse pressure gradient (flat wall) configuration, the VGJs have a similar ensemble-average effect on the boundary layer (Figure 7b). This figure also contains profiles without blowing to highlight the separating boundary layer obtained with adverse pressure gradient conditions. Though the bulk effect on the boundary layer is similar, subtle differences exist in the jet trajectory and lateral diffusion when the flow is decelerating. Figure 8 is a comparison of the jet core trajectory with x/d for the two configurations studied. The diffusion of the freestream flow carries the B=4 trajectory further from the wall while the B=2 trajectory is returned. This may signal jet blow-off at high B values in an LPT application.
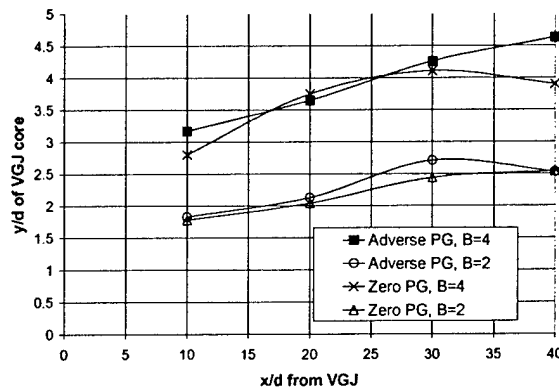

Figure 8: Plot of jet core location vs. x/d for B = 2 & 4 and two flow configurations (no pressure gradient and diffusing flow). Re = 50000.

At the same time, the jet diffuses more rapidly in the cross-stream direction creating a more spanwise uniform boundary layer signature (Figure 9) compared to no pressure gradient (Figure 4).
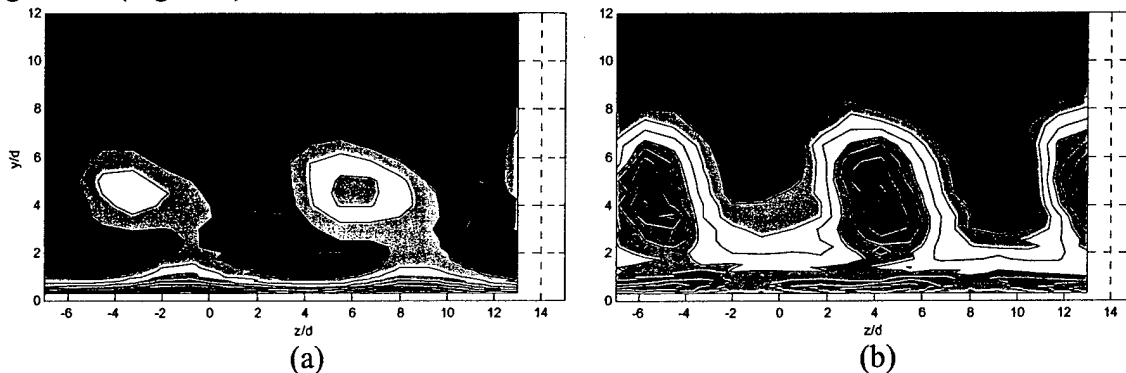

(a)   (b)

Figure 9: Contour maps of (a) streamwise (u/Ue) and (b) wall normal (v/Ue) velocity components at x/d = 40. Re = 50000 and B = 4 into a laminar boundary layer with flat wall and adverse pressure gradient. Compare with Figure 4 data (and colorbars).

The subtle differences created with an adverse pressure gradient suggest that accurately modeling the surface curvature of the LPT suction surface may have a more dramatic effect on jet development. Results to this end are forthcoming.

Future Plans: Testing is currently underway with the wind tunnel in its cascade configuration. The final configuration with suction surface curvature and no pressure gradient will be accomplished subsequently. Following this final configuration, testing will be conducted with elevated freestream turbulence levels. Follow-on research is being planned to investigate unsteady VGJs with a new 3-component PIV system.

Acknowledgement/Disclaimer

References
1. Bons, J., Sondergaard, R., and Rivir, R., 2001, "Turbine Separation Control Using Pulsed Vortex Generator Jets", *ASME J of Turbomachinery*, Apr 2001, pp. 198-206.
2. Sondergaard, R., Bons, J., Sucher, M., and Rivir, R., 2002, "Reducing LPT Stage Blade Count Using VGJ Separation Control," presented at ASME IGTI 2002 in Amsterdam, The Netherlands, paper #GT-2002-30602.

Personnel Supported During Duration of Grant
Richard Eldredge   Graduate Student, Brigham Young University
Jeffrey Bons   Associate Professor, Brigham Young University

AFRL Points of Contact
Rolf Sondergaard and Richard Rivir, AFRL/PRTT, WPAFB, OH, Phone 937-255-7190/2744. Met at IGTI in Atlanta, June 16-19, 2003. Regular correspondence.

Publications, Honors & Awards Received, Transitions, and New Discoveries:
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